Determination of critical water level during first impounding in earth dams using unsaturated transient seepage analyses

Détermination du niveau critique d'eau durant la première mise en eau des barrages de terre par le biais des analyses des infiltrations transitoires non saturées

Amir Akbari Garakani
Niroo Research Institute (NRI), Assistant Professor, Iran

M. Mahdi Shahrabi
Abgeer Consulting Engineers, Geotechnical Engineer,Tehran, Iran

Fardin Jafarzadeh
Civil Engineering Department, Sharif University of Technology, Associate Professor, Tehran, Iran, fardin@sharif.edu

Nina Eskandari, Mehrdad Banikheir
Abgeer Consulting Engineers, Geotechnical Engineer, Tehran, Iran

ABSTRACT: First impounding is one of the most crucial stages in safe operation of earth dams. Lack of an accurate assessment for the rate of raising water level in reservoir may cause instability in upper regions of the dam body or result in excessive and undesirable deformations. Therefore, determination of the safe rate of water level increase during impounding involves a detailed evaluation of both of these issues. In the present paper, results of stability analyses are used to obtain the critical range of impounding level causing the minimum safety factor against failure in the upstream slope of the dam body. The analyses are performed on Silveh Dam, an 89-meter-high (from atop of crest down to foundation level) zoned earth dam with clay core, located in West Azerbaijan Province in Iran. In this regard, by using unsaturated parameters for the clayey core materials, transient seepage analyses are performed and pore pressures induced within the shell and core of the dam are calculated followed by locating the critical slip surface. The results indicate that at a critical range of water level in reservoir, the safety factor against failure reaches a minimum, suggesting that the analysis procedure and results outlined in this study can be implemented in determination of the safe impounding rate for similar projects.

RÉSUMÉ : La première mise en eau est l'une des étapes les plus cruciales pour le bon fonctionnement des barrages en terre. Le manque d'une évaluation précise de la vitesse de l'accroissement du niveau d'eau dans le réservoir peut provoquer une instabilité dans les parties supérieures du corps du barrage ou entraîner des déformations excessives et indésirables. Par conséquent, la détermination du taux sûr d'élévation du niveau d'eau pendant la mise en eau implique une évaluation détaillée de ces deux questions. Dans cet article, les résultats de la stabilité et des analyses de contrainte-déformation sont utilisés pour obtenir la plage critique de niveau de retenue provoquant le facteur de sécurité minimum contre la défaillance dans la pente en amont et les déformations maximales du corps du barrage. Les analyses sont effectuées sur le barrage de Silveh, un barrage de terre zoné de 94 mètres de haut avec noyau d'argile, situé dans la province de l'ouest de l'Azerbaïdjan en Iran. A cet égard, en considérant les paramètres non saturés pour les matériaux de noyau argileux, des analyses d'infiltration transitoires sont effectuées et les pressions de pores induites dans la coquille et le noyau du barrage sont calculées, suivie de la localisation de la surface de glissement critique. Les résultats obtenus indiquent qu'à une plage critique de niveau d'eau dans le réservoir, le facteur de sécurité contre la défaillance atteint un minimum, ce qui suggère que la procédure d'analyse et les résultats présentés dans cette étude peuvent être mis en œuvre pour déterminer le taux de sécurité des projets.

KEYWORDS: first impounding, unsaturated transient seepage, slope stability, earth dam

1 INTRODUCTION

Earth dams are among the most important geotechnical structures composed of various geomaterials with different grading, permeability and strength characteristics. As the body of these geostructures has inclined faces, slope stability analysis during different stages of their construction and operation is of particular significance. The stability of dams and other slopes is typically calculated using Limit Equilibrium (LE) method (Fredlund 1984; Duncan 1996; Morgenstern 1992). Conventionally, the stability of an earth or rockfill dam's upstream and downstream slopes and stress-deformation of the dam body are evaluated during various loading conditions (after construction, constant seepage, rapid drawdown, dynamic loadings) for all of which, a specific factor of safety against failure has been suggested in the literature (USBR 1987; BRE 1990; NGI 1992; Garakani 2005 and Jafarzadeh and Garakani 2013). However, one of the most important stages during an earth dam's operation, which is mostly overlooked in terms of slope stability analysis, is the first impounding stage. As calculated by LeBihan and Leroueil (2000), full saturation and constant seepage may take up to a decade in an earth dam with central core with average permeability of 10^{-7} m/sec. Therefore, an unsaturated transient seepage condition takes place through the dam body during the impounding stage. Since undrained conditions occurs in even low rates of raising the water level in dam's reservoir (Cooper et al. 1997; Fell et al. 2005), pore pressures are subject to increase during impounding, causing a reduction in the factor of safety. Therefore, determination of the critical water level during the first impounding stage in earth dams seems to be crucial to evaluate the stability of these huge geostructures.

In this study, slope stability analyses during the first impounding of a recently constructed earth dam (Silveh dam) were performed using the results of unsaturated transient seepage analysis and the effect of impounding on the stability of upstream slope was evaluated.

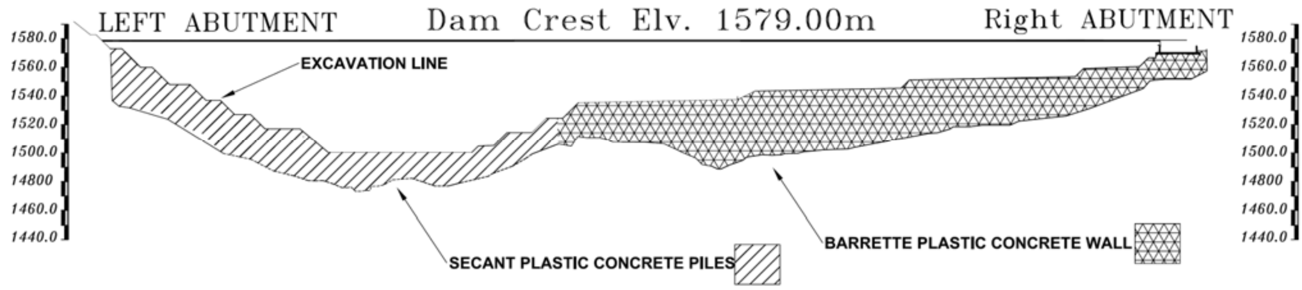

Figure 1. Longitudinal cross section of Silveh dam

2 SITE CONDITIONS AND DAM CHARACTERISTICS

Silveh Dam is a recently constructed zoned earth dam located about 12 km northwest of Piranshahr in the Western Azerbaijan Province, Iran. Feasibility studies of dam construction on the Lavin-Chai river started in 1975 and Phase-I studies and geotechnical site investigations were completed in 2002 with more than 1353 meters of boring. General and engineering geology studies demonstrated that the dam site is located on the Sanandaj-Sirjan Belt, a few kilometers away from the active strike-slip Piranshahr Fault, subjecting the dam foundation to folding, faulting and magmatism. Additionally, paleoseismological studies and recorded seismic events proved that the occurrence of strong earthquakes with a shallow focus (10-15 km) should be taken into account for design of the dam body, where the Maximum Credible Earthquake (MCL) is predicted to cause strong ground motion with a 0.465g peak horizontal acceleration.

The dam body is placed on a wide valley which comprises a coarse-grained alluvial deposits with maximum of 65 m depth in right bank and limestone or schist rock in left bank, underlain by a layer of lightly metamorphosed limestone and shale with lenses of slate, metamorphic sandstones, and powdered layers of schist and mica schist. The capacity of the dam reservoir, at its normal water level (1573.5 m a.s.l.), is about 89 million cubic meters. With a crest level of 1579 m a.s.l., the maximum height of the dam is approximately 89 meters and its crest length is near 720 meters. Therefore, by considering the crest length to dam height, two-dimensional (2D) plane strain slope stability analysis was assumed to give accurate results. In order to control seepage through the dam foundation, a combination of barrette wall and secant piles made of plastic concrete with about 45 meters maximum depth was implemented (Fig. 1). The maximum section of Silveh dam is shown in Figure 2. Due to high level of seismicity at the dam site, slopes between 1V:2.15H (upper portion) and 1V:4.5H (lower portion of the upstream) were designed for the body of the dam. The foundation in this section is completely composed of rock material. As shown in Figure 2, the dam body encompasses different zones, including a clay core and an impervious upstream blanket, upstream and downstream shells of coarse-grained gravelly sand, drain and filter. The fill material properties are summarized in Tables 1.

Table 1. Shear strength and density properties of the fill materials

	Cohesion, c (kPa)	Internal friction angle, φ (degree)	γ_{sat} (kN/m^3)	γ_{wet} (kN/m^3)
Core (CD)	6	33	-	19
Core (UU)	28	5	20	-
Shell	7	41	22	20
Filter	0	32	22	20
Drain	0	35	22	20

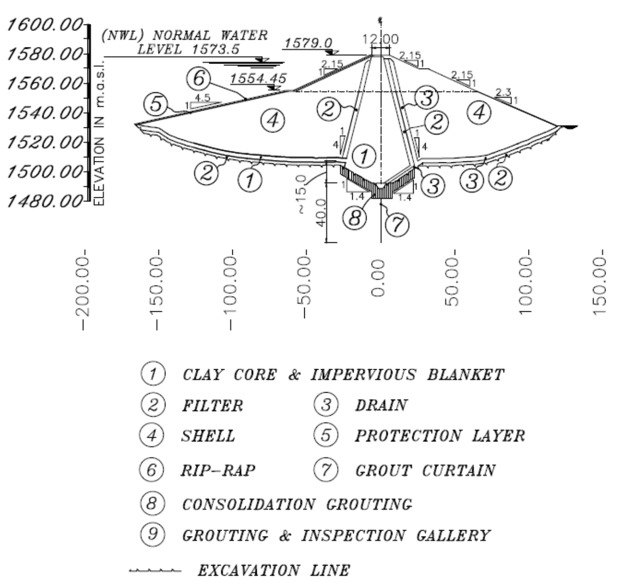

Figure 2. Maximum height cross section of Silveh Dam

3 FIRST IMPOUNDING AND TRANSIENT SEEPAGE ANALYSIS

During the construction of Silveh Dam, water level in the reservoir was kept constant, approximately up to the level of the cofferdam crest (1526 m a.s.l.). For the first impounding of the dam, a specific time plan was proposed and numerically evaluated (using Geostudio software) to guarantee safe operation of the dam. In this regard, the water level is initially raised to 1535.2 m a.s.l. at a rate of 1 meters per day, followed by 14 days of keeping the water level constant. Thereafter, the water level was once again raised at a rate of 1 meters per day to the level of the upstream stabilizing berm (1554.45 m a.s.l.). After another break for 14 days, the water level was raised to 1573.5 m a.s.l., the normal water level of the dam reservoir, at a rate of 0.5 meters per day. The proposed impounding time plan, which took 95 days, is also schematically shown in Figure 3.

In order to determine the water infiltration trend through the dam body and the resulting seepage forces due to first impounding, a set of unsaturated transient seepage analyses were carried out. The unsaturated soil parameters used for seepage analysis are summarized in Table 2 and Figure 4 for coarse-grained and fine-grained geomaterials, respectively. It should be mentioned that the equations proposed by van Genuchten (1980) were applied for estimation of volume water content and hydraulic conductivity of the core and filter materials at different matric suctions. Typical results obtained by the two-dimensional finite element (FE) seepage analyses are shown in Figure 5. The phreatic and equipotential lines before and after the first impounding are depicted in this figure. By comparing Figures 5 (a) and 5(b), it can be observed that right after the impounding finishes, the water has not yet infiltrated the core, which is attributed to very low permeability of clay material. Hence, two separate zones can be detected inside the dam core below (saturated) and above (unsaturated) the level of water. The unsaturated portion of the core is therefore subjected to an undrained type of external loading that increases the pore pressures, which governs the type of shear strength parameters that should be used in stability analyses. In case the first impounding starts long enough after the dam construction, where most of the excess pore pressures has dissipated, Consolidated Undrained (CU) shear strength parameters should be used for the unsaturated portion of the dam core in stability analysis. However, if the first impounding starts before dissipation of the excess pore pressures, the clay core will be subjected to Unconsolidated Undrained (UU) loading condition. Considering the amount of excess pore pressures in the core of Silveh Dam before impounding (measured by the installed piezometers), UU shear strength parameters were applied to the unsaturated portion of the dam core in stability analyses (Table 1).

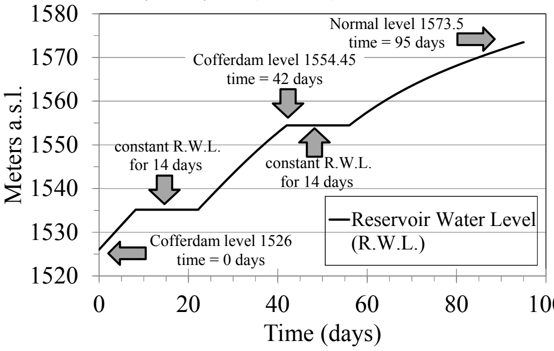

Figure 3. Variation of reservoir water level with time for the proposed first impounding time plan for Silveh Dam

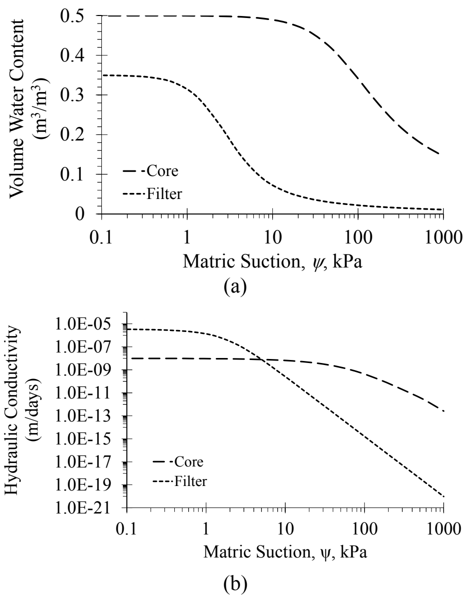

Figure 4. Unsaturated soil parameters of core and filter materials; (a) soil water retention characteristics (SWRC), and (b) hydraulic conductivity curves.

Table 2. Transient seepage analysis parameters

	Coarse-grained soils and rock			
	Shell	Drain	Bedrock	Cut-off wall
Permeability (m/day)	1.15×10^{-4}	1.15×10^{-3}	1.0×10^{-7}	1.0×10^{-9}

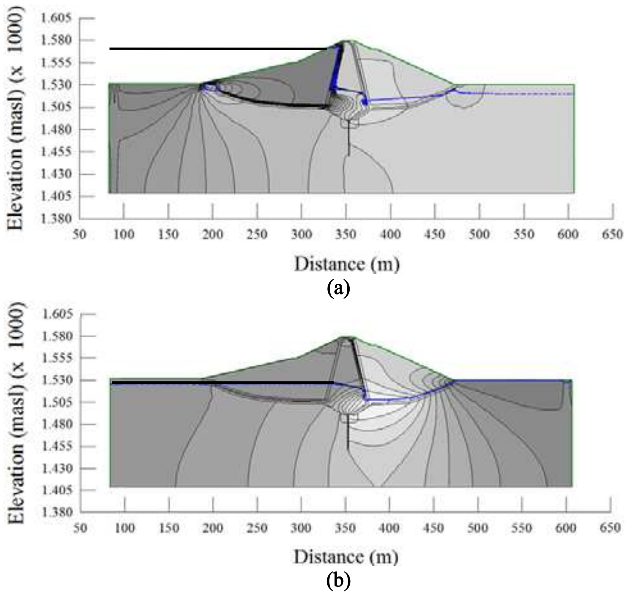

Figure 5. Phreatic and equipotential lines obtained from unsaturated transient seepage analyses; (a) before, and (b) after the first impounding.

4 SLOPE STABILITY MODELS

The results obtained from the transient seepage analyses were implemented as the basis for static and dynamic stability analyses of Silveh Dam's upstream slope. Implementing Limit Equilibrium (LE) method, safety factors (FS) against instability were calculated (using Geostudio software) at different reservoir water levels. Among the numerous proposed approaches to slope stability assessment, the method described by Morgenstern and Price (1965) was used in the present study. As previously indicated, UU and CD shear strength parameters were applied to the portions of the dam core above and below the phreatic line, respectively (Table 1). Stability analyses of the dam's upstream slope were carried out from the start until completion of reservoir impounding at periods of 5 days (totally 18 stages). The results of LE slope stability analyses for the pre- and post-impounding conditions are presented in Figures 6(a) and 6(b), respectively.

Figure 7 shows variations of the reservoir water level and the slope stability safety factor with the impounding duration. It is observed from this figure that the safety factor is almost constant during the first phase of impounding (F.S.≈ 2.15). By raising the water level, F.S. is detected to drop to a minimum of 1.95, before again increasing to become 2.07, which is attributed to the gradual dissipation of excess pore pressures inside the dam core. The interactive increasing and decreasing effects of the reservoir water level (in increasing the pore pressures in core materials and in exerting a retaining pressure to the upstream face of the dam body), causes F.S. to have a minimum value at a specific point depending on the rate of impounding. The obtained results show that the minimum static safety factor during the first impounding stage is well above those suggested in the literature, proving the suitability of the proposed impounding time plan. The reason behind high values of the static safety factor for Silveh Dam is that the seismic loading conditions were the controlling ones for design of the dam. It should be noticed that although the minimum safety factor during the impounding stage was found not to be critical for the specific dam studied in this paper, the stability condition in this stage may be determinative for some dams. Therefore, it seems that the effect of the rate of impounding should be taken into account when estimating the stability of earth embankment dams.

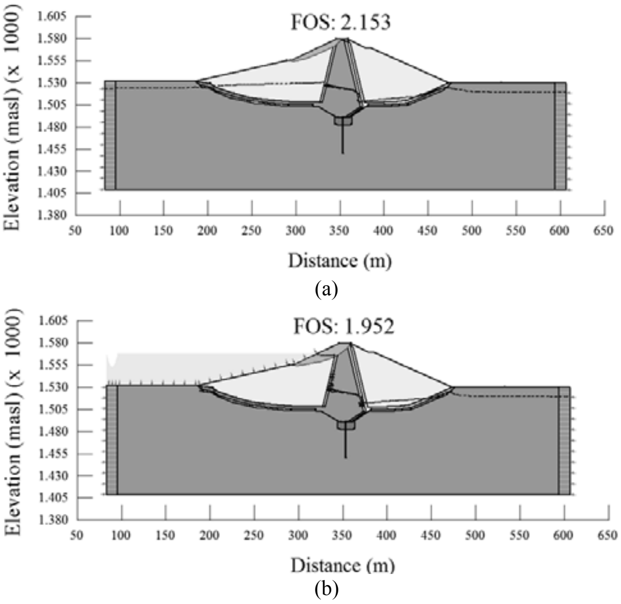

Figure 6. Minimum safety factors obtained from limit equilibrium slope stability analyses; (a) before impounding, and (b) at the critical water level.

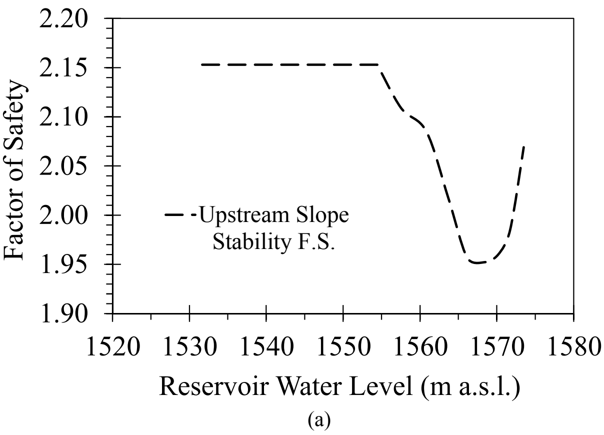

Figure 7. Variation of safety factor against upstream slope instability with reservoir water level.

5 CONCLUSIONS

In the present paper, results of unsaturated transient seepage and slope stability analyses were used to portray the influence of the rate of raising the water level on the stability of an earth embankment dam during first impounding. Analyses were performed on a typical section of Silveh Dam, a recently constructed zoned earth dam located near the city of Piranshahr in the Western Azerbaijan Province, Iran. It was shown that by raising the water level in reservoir and as a result of an increase in pore pressures inside the dam core, the safety factor against instability of Silveh Dam's upstream slope dropped to a minimum value during the impounding stage, suggesting that the rate of impounding plays an important role in stability of earth embankment dams. The impounding time plan proposed for Silveh Dam were found to secure the minimum safety factor for slope stability analyses.

6 REFERENCES

Building Research Establishment (BRE) 1990. *An engineering guide to the safety of embankment dams in the United Kingdom*. Garston, UK.

Duncan J.M. 1996. State of the art: limit equilibrium and finite element analysis of slopes. *J. of Geotech. Eng. ASCE* 122 (7), 577–591.

Fell, R. MacGregor, P. Stapledon, D. and Bell G. 2005. *Geotechnical Engineering of Dams*. Taylor & Francis, London, UK.

Fredlund D.G. 1984. Analytical methods for slope analysis. *Proc. 4th International Symposium on Landslides*, Toronto, 229–250.

Garakani. A.A. 2005. 2D and 3D numerical analysis of the sliding abutment effect on the stress - deformation behavior of rockfill dams during construction, first filling and rapid draw down (A case study - Upper Gotvand Dam), MSc thesis, Sharif University of Technology, Tehran, Iran.

Haeri, S. M and Garakani, A.A 2012. 3D Analysis of the Effect of the Sliding Abutment on Stress –Deformation of the Rockfill Dams at the End of Construction and First Impounding, The First International Conference on Dams & Hydropower, 10-12 Feb 2012, Tehran, Iran

Jafarzadeh,F. and Garakani, A.A. 2013. Foundation Treatment in Rockfill Dams with Consolidation Grouting, Seventh International Conference on Case Histories in Geotechnical Engineering and Symposium in Honor of Clyde Baker. April 29 - May 4, 2013, Chicago, USA.

LeBihan J.P. and Leroueil S. 2000. *Transient water flow through unsaturated soils – implications for earth dams*. REGIMA.

Morgenstern N.R. 1992. The evaluation of slope stability – a 25 year perspective. In stability and performance of slopes and embankments, *Geotechnical special publication* 31 (1), 1–26.

Morgenstern N.R. and Price V.E. 1965. The analysis of the stability of general slip surfaces. *Geotechnique* 15(1), 79-93.

Norwegian Geotechnical Institute (NGI) 1992. *Rockfill dams, design and construction*. Kjaernsli, B. Valstad, T. and Höeg, K., Norwegian Geotechnical Institute, Norwegian Institute of Technology, Oslo.

US Bureau of Reclamation (USBR) 1987. *Embankment Dam Instrumentation Manual*. Denver, US.

van Genuchten M.Th. 1980. A closed-from equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America* 44, 892-898.